FAST FLAME CONTROL BY NANOSECOND BARRIER DISCHARGE

E.I. Mintoussov, A.A. Nikipelov, A.V. Krasnochub, S.M. Starikovskaya, A.Yu.Starikovskii
Physics of Non-Equilibrium Systems Laboratory,
Moscow Institute of Physics and Technology, Dolgoprudny, 141700, Russia

Abstract

The efficiency of nanosecond discharges as active particles generator for plasma assisted combustion and ignition has been investigated. The study of nanosecond barrier discharge influence on a flame propagation and flame blow-off velocity was carried out. With energy input negligible in comparison with burner's chemical power, a double flame blow-off velocity increase was obtained. The present paper shows that, besides proper form of energy input, proper organization of discharge is of great importance. It was found that active particles (O and OH primarily), which are produced in the streamer head under its action, play the most significant role in the effect of combustion acceleration. The model of flame acceleration, suggested in the previous work, was confirmed by the new experimental data.

Introduction

The problem of the uniform ignition and efficient combustion of a gas mixture is of crucial importance from both scientific and technological standpoints. The oxidization of a fuel proceeds via a chain mechanism, which is very fast. The delay time of ignition is limited by the rate at which active centers are produced, usually by thermal dissociation. For this reason, the total rate of reaction is, in fact, higher with artificial initiation of a chain. The easiest way to produce free radicals is to decompose the weakest bond of a molecule.[1] The two mechanisms by which a discharge can affect a gas should be taken into account when using a discharge to initiate combustion. For discharges resulting in the formation of an equilibrium (or nearly equilibrium) plasma (e.g., sparks and arcs), the main factor that reduces the delay time of ignition is local heating of gas and, accordingly, the increase in rate of thermal dissociation.[2–4] In the case of a nonequilibrium plasma, the main mechanism initiating chain reactions is dissociation and excitation of molecules by electron-impact. The question of the efficiency of using nonequilibrium plasmas still remains open despite of the fact that theoretically even relatively small amount of atoms and radicals ($\sim 10^{-5}$–10^{-3} of the total number of the gas particles) can shift equilibria in the system and initiate a chain reaction.

In this paper the study of pulsed nanosecond barrier discharge influence on flame blow-off velocity was performed. It was found that proper organization of discharge is crucial for effective flame control. It's necessary to provide the production of OH radicals in a certain place of the flame for maximum effect. The main characteristics of successful energy input, in this case, is the maximum value of the ratio of flame blow-off velocity with discharge to that one without discharge (instead of maximum possible flow speed), and the minimal ratio between discharge energy input and chemical power of a burner.

Combustion Experiment

The main part of the experimental setup is a quartz nozzle with rectangular section. Three different nozzles, with 2.2, 2.5 and 4.3 mm in width and the same length of 30 mm were investigated. Stainless steel 0,8 mm thick high-voltage electrode was placed inside the nozzle, and the grounded electrodes were situated near the nozzle edges, parallel to them. In order to prevent a transition of the discharge into a spark form, they were set tightly into quartz tubes. On applying a voltage to the gap, a barrier discharge occurred, so the maximum possible current was limited by the dielectric. You can find more detailed description of the setup in.[5]

To fix the point of streamer start and the number of streamers as well, the high-voltage electrode has a number of pins on its upper edge. Two electrodes were used - with 8 and 15 pins, so the number of streamers could be 16 or 30 respectively. The nozzle and images of discharge and flame are presented in fig.1.

Earlier it was shown by the authors in[5] by picosecond ICCD camera images that the energy inputs in the mixture only during the first 10-20 ns of pulse duration, and then the region of energy release moves beyond the zone of mixture flow and is situated near the grounded electrodes. To increase the effectiveness of energy input, the principal scheme of high-voltage generator has been changed entirely. Instead of rotation interruptor scheme with pulses of 77 ns FWHM, we used the idea of magnetic compression to reduce the pulse length. In the present work we used three different types of pulses: with FWHM 7, 19 and 24 ns. The voltage on the discharge gap could be 14 kV or 22 kV, the nanosecond pulse polarity was positive. Pulse repetition rate could be varied within the range of 400-1000Hz.

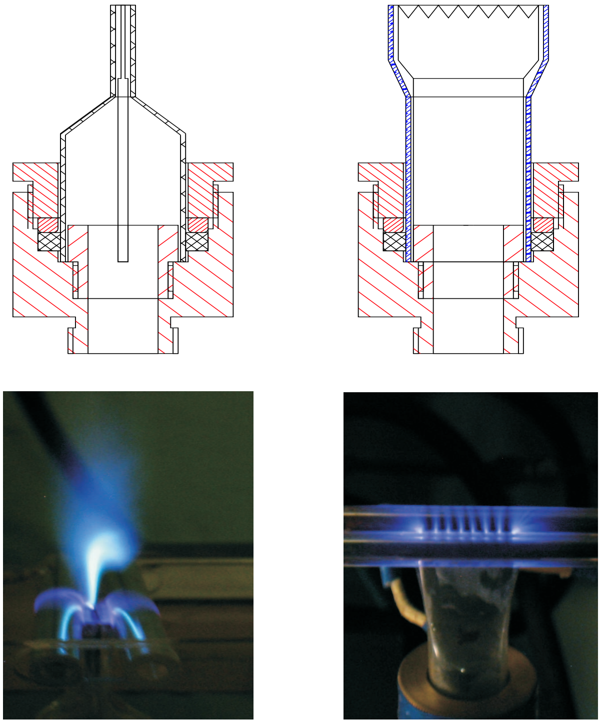

Figure 1: Quartz nozzle and discharge view

The investigations of active particles production were performed by emission spectroscopy methods. The recording facility consisted of CCD-line (spectral range of $\lambda = 200–800$ nm) and MDR-41 monochromator (with an operating range of $\lambda = 190–600$ nm and a linear dispersion of 0,96 nm/mm). The optical system was calibrated using a standard emission source (a calibrated DDS-30 deuterium arc lamp emitting in the range 190–500 nm).

Combustion. Results and Discussion

It was shown in,[1] that in processes of combustion acceleration and flame velocity increase the main role is played by active particles (such as O, H, OH and so on), which are responsible for chain branching. The production of additional centers results in acceleration of chemical kinetic processes. Another important feature is the proper organization of energy input. The energy should be put inside the gap and lead to radical production (instead of gas ionization or thermal heating). Streamer type of discharge totally corresponds to these condition. The main area, where active particles are produced, is the streamer head, which is quite small (~ 0.05 cm for typical voltages of 10–20 kV[6]), but has high values of reduced electric fields (up to 800 Td).

We used two different high-voltage electrodes - with 8 and 15 pins. In fig 2 and fig 3 the comparison of the discharge influence on propane-air flame blow-off velocity is shown. It's seen quite well that both types of electrodes lead to flame acceleration for the cases of 14 kV and 22 kV. But the effectiveness of such influence is different - the effect is greater for 15-pin electrode (Fig.4), because of the larger quantity of streamer. So, the flame stabilization occurs due to the plasma action and hardly depends on the local overheating near the steel plate pins, because estimations shows that overheating is greater in case of 8-pin electrode.

The energy input in both cases was the same and was equal approximately to 2-5 mJ per pulse (2-5 W of total power). This value corresponds to 0,5% of the chemical power of the burner. The equivalent value of gas heating by this energy is 10-20 K. This fact confirms the thesis about the importance of the way we put energy in the mixture.

We just have showed that if we are making pulse shorter (24 ns vs 77 ns in the previous work[5]), we

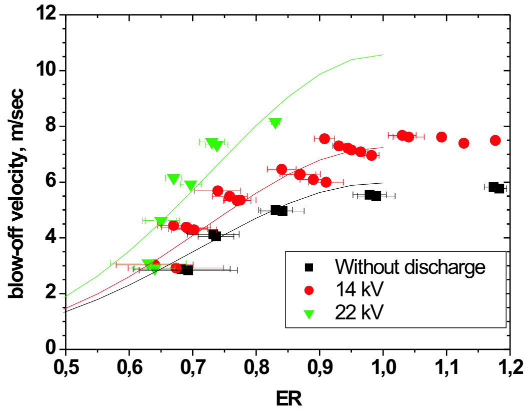

Figure 2: Flame blow-off velocity increase with 8-pin HV electrode

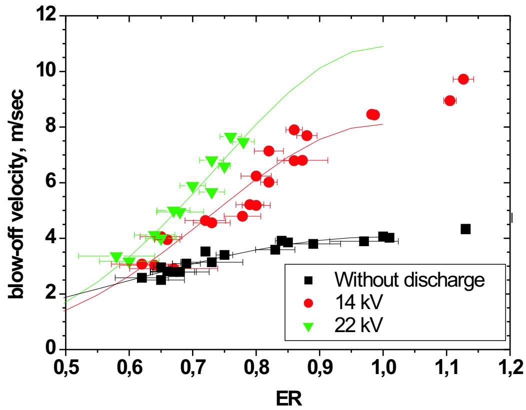

Figure 3: Flame blow-off velocity increase with 15-pin HV electrode

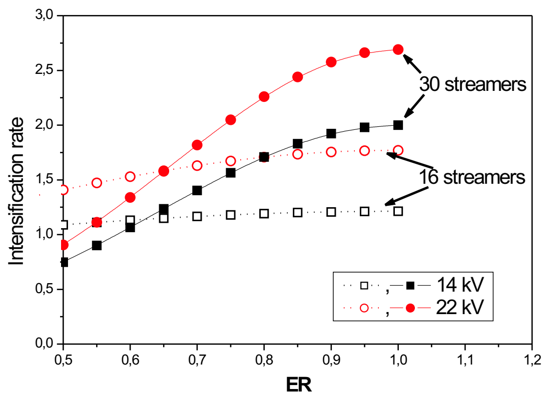

Figure 4: The comparison of the effectiveness of influence. 8-pin versus 15-pin HV electrode

can increase the efficiency of energy input (we've reduced energy input more than 2 times, and still have the same increase in flame blow-off velocity). But the duration of pulse should be greater than the time of streamer propagation through the gap where mixture flows, to provide full overlapping of the nozzle by the streamer. The streamer velocity was calculated in,[6] and is equal to 0.6 mm/ns under the voltage of 22 kV, so in the case of 14 kV, as in our experiment, the velocity value is even lower. On the images (Fig.5) it is shown that in the regimes near blow-off point streamer prefers go through the weakly ionized zone just below the flame instead of the shorter way. Calculations were made for the time of the gap overlapping, and the result is approx. 8 ns in the case of 2 mm nozzle (track length is 5 mm), and even greater in the case of 4.3 mm nozzle.

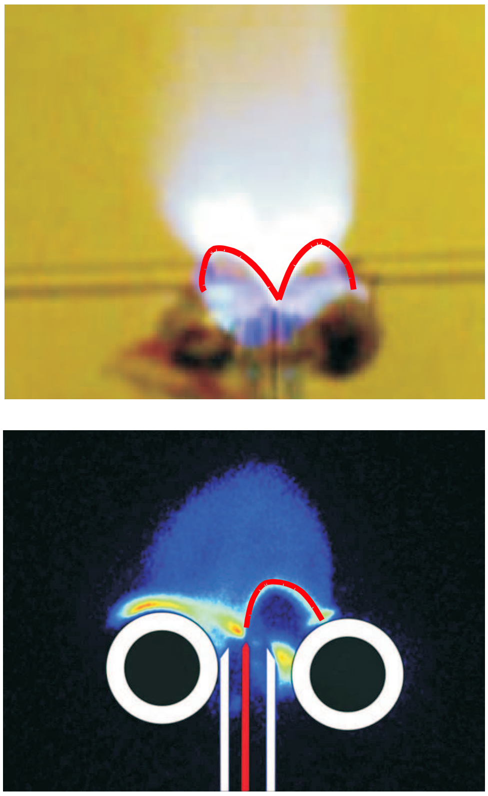

Figure 5: The streamer track in the gap. Top image was obtained by common camera, bottom one - by ICCD picosecond camera, the gate is 1 ns

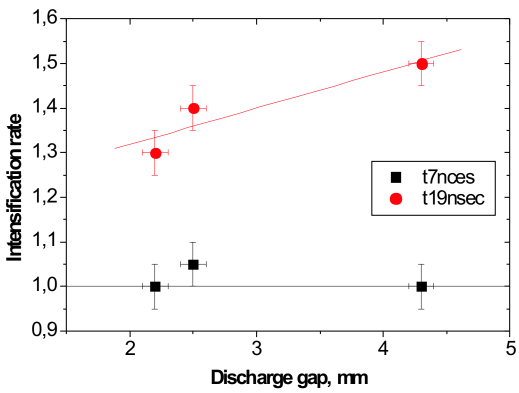

Figure 6: The discharge influence on flame blow-off velocity for different pulse durations

To confirm these arguments, a number of experiments has been performed. Two types of additional line pieces were used to provide different pulse duration (FWHM 7 ns and 19 ns). It was found that at frequency 500 Hz and ER=0.8 19 ns pulse is much more efficient than 7 ns one for all three nozzles, and the advantage of using 19 ns grows with nozzle widening (Fig.6), as it was predicted earlier.

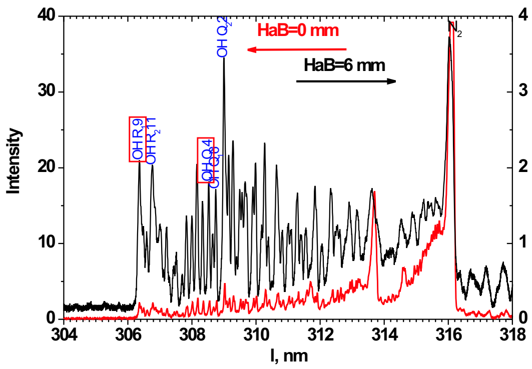

Figure 7: OH* spectra in methane-air flame under discharge action at HaB=0 mm and HaB=6 mm

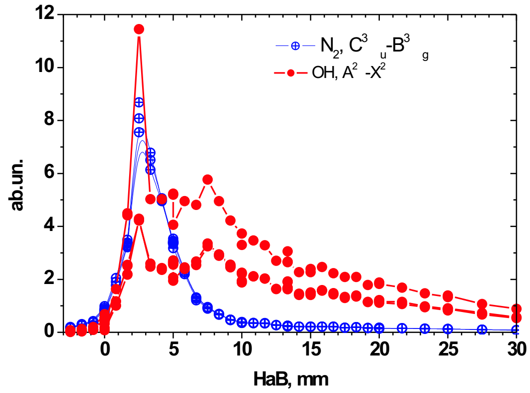

Figure 8: OH* profile along the HaB in methane-air flame

A series of experiments were made to prove the correctness of the model of flame acceleration and kinetic scheme, suggested in the previous work.[5] It's worth to remind that, according to,[5] the main role is played by radicals, which appears under the non-equilibrium nanosecond discharge action. That's why it's very important to make spectroscopic investigation of the flame itself and the flame under discharge action. In,[5] the profile of OH radical along the height above burner in propane-air flame was presented. That result was based on the non-resolved spectrum (OH($A^2\Sigma, v' = 0 \rightarrow X^2\Pi, v'' = 0$)) at 306.4 nm with quite a large apparatus function of monochromator (2.4 nm). This caused a question, is the first peak of the typical "two-humped" spectrum connected with N_2 production in the discharge (second positive system of nitrogen $C^3\Pi_u \rightarrow B^3\Pi_g$ has intense lines on the wavelengths of 315.9 nm (1→0), 313.6 nm (2→1) and 311.6 (3→2))? In the present work, using CCD-line with signal accumulation mode, it became possible to obtain rotationally resolved spectrum of OH radical in methane-air flame. The spectra of OH* for two different heights (0 mm and 6 mm) above the burner are presented in fig.7. It's distinctly seen that in the region below 310-312 nm we can use any rotational line of OH* spectrum to build the dependence between OH* emission and height above burner (HaB). The result is presented in fig.8, and this figure confirms the previously obtained one for propane-air mixture as well as the importance of OH radical in flame and the similarity of kinetic processes, which lead to flame blow-off velocity increase, for the vast majority of premixed hydrocarbon-air flames. The results for methane-air flame blow-off velocity increase (fig.9) are in agreement with this theory.

Using OH rotationally resolved spectra, the rotational temperature was calculated. The technique of temperature determination is described in.[7] We used the ratio of $R_1(9)$ (λ=306.3565 nm) line and $Q_1(4)$ (λ=308.3278 nm) line. In the case of equilibrium flame, the rotational temperature, obtained in a such way, is close to the translational temperature (the radiative time of living of $A^2\Sigma$ level is 690 ns,[8] and the typical time between particles collisions is about 30 ns, so the Boltzmann distribution of particles

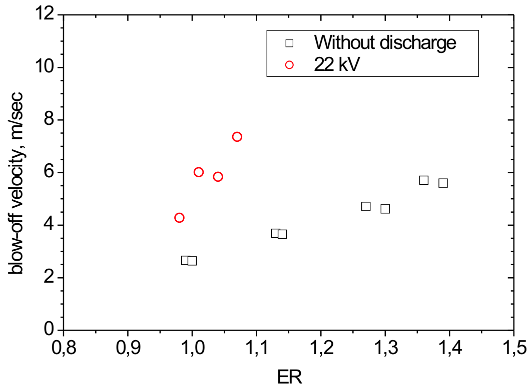

Figure 9: Methane-air flame blow-off velocity increase

at rotational levels occurs before radiation). Experimental OH rotational temperature profiles along the height above burner in methane-air flame are presented in fig.10

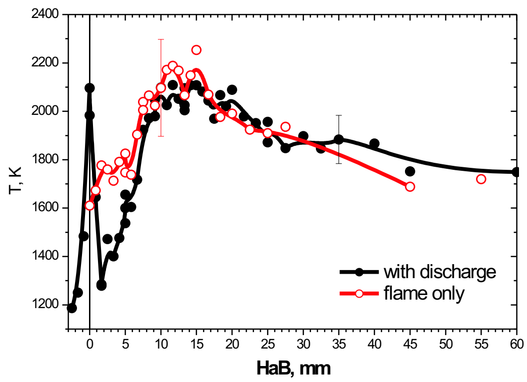

Figure 10: Experimental OH rotational temperature profile along the HaB in methane-air flame

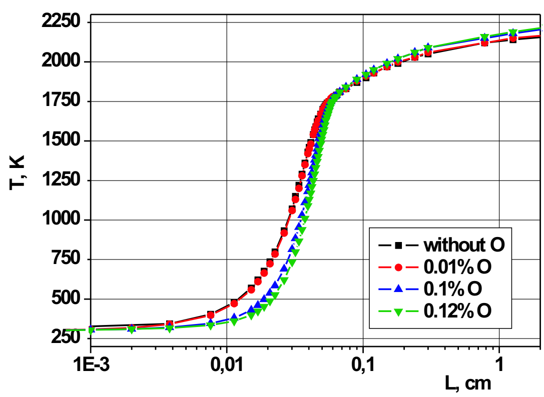

Figure 11: Calculated temperature profile along the HaB in methane-air flame

The comparison of experimental profile with calculated one shows a good data agreement. The theoretical model is based on changing in initial mixture composition under the discharge action.

An additional proof to the suggested theory and the model of radical influence lies in the results of experiments with $Ar/O_2/C_3H_8$ mixture. We have changed the nitrogen in the mixture to argon in order to prevent active particles formation. According to the model, the main channel of O and OH production is the quenching of electronically-exited triplet states of N_2 on the oxygen molecules in processes:

$$N_2(A^3\Sigma_u^+) + O_2 \rightarrow N_2(X^1\Sigma_g^+) + O + O; \quad (1)$$
$$N_2(B^3\Pi_g) + O_2 \rightarrow N_2(X^1\Sigma_g^+) + O + O; \quad (2)$$
$$N_2(C^3\Pi_u) + O_2 \rightarrow N_2(X^1\Sigma_u^+) + O + O; \quad (3)$$
$$N_2(a'^1\Pi_g) + O_2 \rightarrow N_2(X^1\Sigma_u^+) + O + O. \quad (4)$$

or dissociation of oxygen molecule, which can proceed via its electronically excited states:

$$O_2(\text{el.exc.}) \rightarrow O(^3P) \ + \ O(^3P); \quad (5)$$
$$O_2(\text{el.exc.}) \rightarrow O(^3P) \ + \ O(^1D). \quad (6)$$

So, the substitute of nitrogen to argon should reduce the amount of atomic oxygen and decelerate flame in comparison with $N_2/O_2/C_3H_8$ mixture. Indeed, the results (fig.12) showed that the phenomenon in argon mixture is much more weaker. This is an evidence for our flame acceleration model.

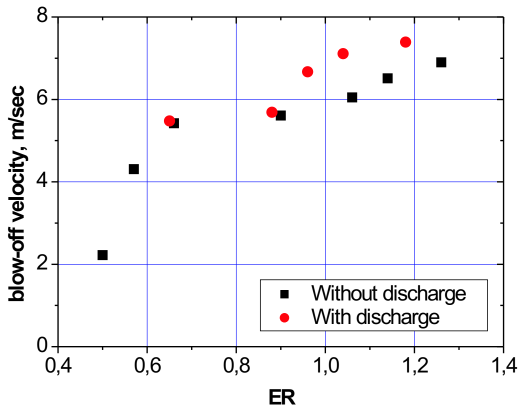

Figure 12: Flame blow-off velocity increase for $Ar/O_2/C_3H_8$ mixture

PLIF OH Measurements

To investigate formation of OH radicals by nanosecond discharge we have adjusted laser induced fluorescence technique. Experimental setup and details of adjustment procedure is represented in Fig.13 (a, b). Laser emission at 281 nm was used to obtain fluorescence of OH. The emission was produced by laser system concerning NdYAG laser at second harmonics and dye laser with doubling system. System with cylindrical lenses was used to get 2D map of fluorescence. Laser wavelength was adjusted with the help of simultaneous registration of laser wavelength and rotational system of OH emission from propane-air premixed flame (typical plot used for adjustment is demonstrated in Fig.13a). The fluorescence was registered by with a PicoStar HR12 (La Vision) ICCD camera with interference filter (315 nm with width 1.8 nm at the half-height). Camera gate was 30 ns. Camera was synchronized with NdYAG laser operation.

Comparison of OH* emission (obtained with the same interference filter) from the burner and 2D OH fluorescence (Fig.13b and 13c respectively) demonstrates significant difference in a spatial distribution of excited OH radicals and OH in the ground state even at absence of the discharge.

The formation of secondary OH peak in the discharge zone corresponds with the statement that place where the active particles are put is important. It's useless to produce radicals in the reaction zone, where temperature is high enough and radical production in discharge is negligible with that one in chain

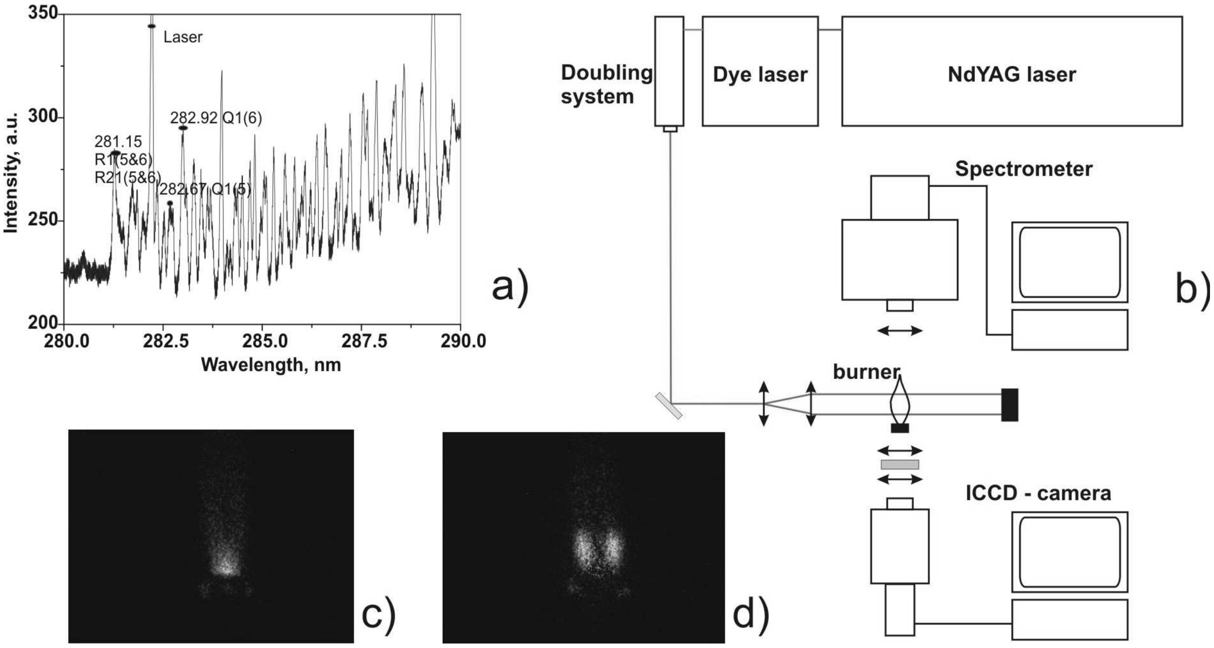

Figure 13: Scheme of the experimental setup. a) - spectrum of OH emission from the burner with superposed laser emission; b) - scheme of experimental installation; c) - typical OH* emission from propane-air premixed flame; d) OH PLIF-image at the same experimental conditions.

reactions. On the other hand, if radicals are produced before reaction zone at a large distance, they probably recombine and just heat the gas for a few decades of K. So, an optimal place exists, where radical production is most effective in terms of flame blow-off increase.

So, there are two types of discharge application in combustion tasks. The first is to ignite mixture in areas with low flow speed with combustion rate remaining constant, i.e., by heating and the second is to increase combustion rate by uniform treatment of mixture in the discharge. We think that the second way is more perspective and that's why one should use relative flame velocity increase as the main parameter of discharge effectiveness, instead of absolute values of flow speed. We should compare the discharge power to relative burner power increase, taking into account that completeness of combustion could change. Our results show that flame propagation velocity can be increased more than twice, depending on the way we organize discharge as well as discharge parameters (duration, pulse repetition rate, voltage etc). The intensification ratio (blow-off rates ratio with and without discharge) is significantly higher when greater number of streamers is used. Results for different pulse durations confirm idea about importance of number of active particles which are produced under the discharge action.

Conclusion

The study of efficiency of nanosecond discharge plasma on combustion and ignition process has been carried out. The following conclusions could be made:

For nanosecond plasma assisted combustion, with energy input negligible in comparison with burner's chemical power, a double propane-air flame blow-off velocity increase was obtained. It was shown experimentally that the results for methane-air flame are similar with propane-air one. Besides proper form of energy input, proper organization of discharge is of great importance. It was found that the effectiveness of plasma-assisted combustion depends on type of discharge, pulse duration, pulse repetition rate and other parameters, which are responsible for active particles production. It was found that active particles (O and OH primarily), which are produced in the streamer head under its action, play the most significant role in the effect of combustion acceleration. The model of flame acceleration, based on nitrogen quenching on oxygen molecules, with production of O and OH radicals, was confirmed by the new spectroscopic investigations and experiments with $Ar/O_2/C_3H_8$ mixture, where discharge influence is small because of the absence of mechanism of active particles production.

Acknowledgments

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